

2-Way Simultaneous Doppler and Ranging for Multiple Spacecraft at Mars

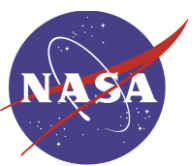
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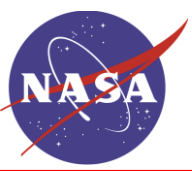
Outline of Talk

PART 1 - BACKGROUND AND SYSTEM CONCEPT

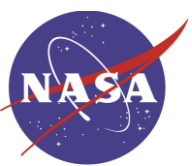
- **OVERVIEW OF THE PROPOSED MARS REGIONAL NAVIGATION SATELLITE SYSTEM (MRNSS)**
- **IMPORTANCE OF ACCURATE NAVIGATION SATELLITES ORBIT DETERMINATION (OD)**
- **CHALLENGES OF DEEP SPACE TRACKING/NAVIGATION FOR MULTIPLE SPACECRAFT**

PART 2 - SIMULTANEOUS 2-WAY DOPPLER/RANGING

- **SYSTEM APPROACH: A COLLABORATIVE FLIGHT-GROUND ARCHITECTURE**
- **DIFFERENT DOPPLER AND DOPPLER RATE OF MARS ASSETS**
- **SIGNAL STRUCTURE: RELATIONSHIP BETWEEN CARRIER FREQUENCY AND RANGE CLOCK**
- **FLIGHT RADIO UPGRADE: SMART SWEEPING ALGORITHM**
- **GROUND PROCESSING: MULTIPLE COPIES OF RECEIVER RANGING PROCESSORS (RRP's)**

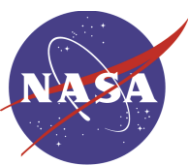


Part 1: Background and System Concept

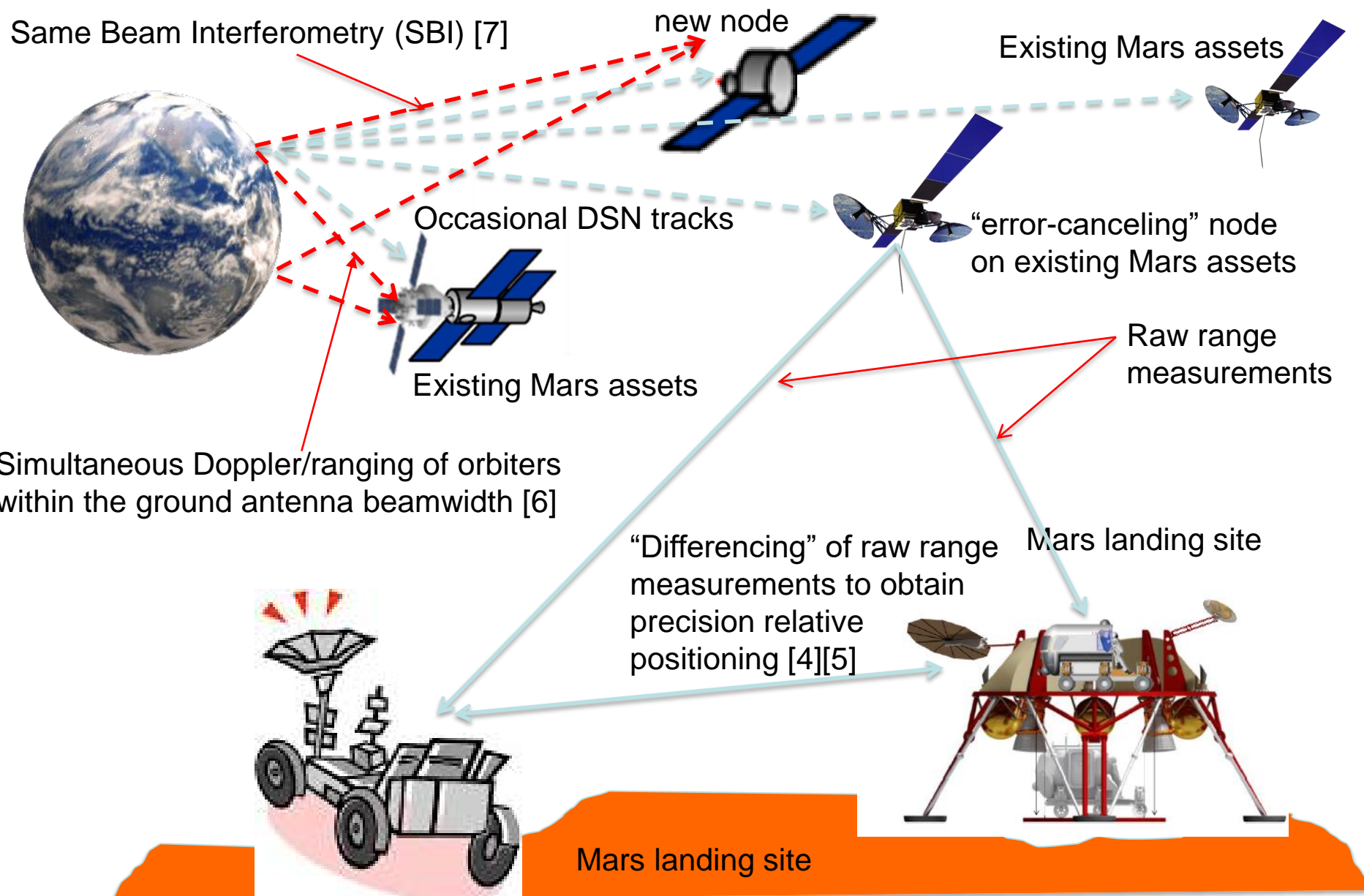


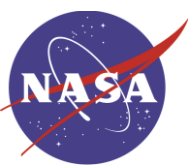
Proposed Mars Regional Navigation Satellite System (1)

- We have been working on the system concept of a low-cost low-maintenance Mars Regional Navigation Satellite System (MRNSS) [1] with the following key principles
 - Capitalize on the build-up of orbiting and surface infrastructures on Mars during the human Mars exploration era [2][3][4]
 - Leverage on a new geometric trilateration method that simultaneously performs absolute positioning and relative positioning [5][6]
 - Introduce the concept of using relative positioning that provides regional navigation services in the vicinity of a human Mars landing site (~100 km), thereby relieving the stringent requirements on orbit determination (OD) of Mars navigation satellites



Proposed Mars Regional Navigation Satellite System (2)

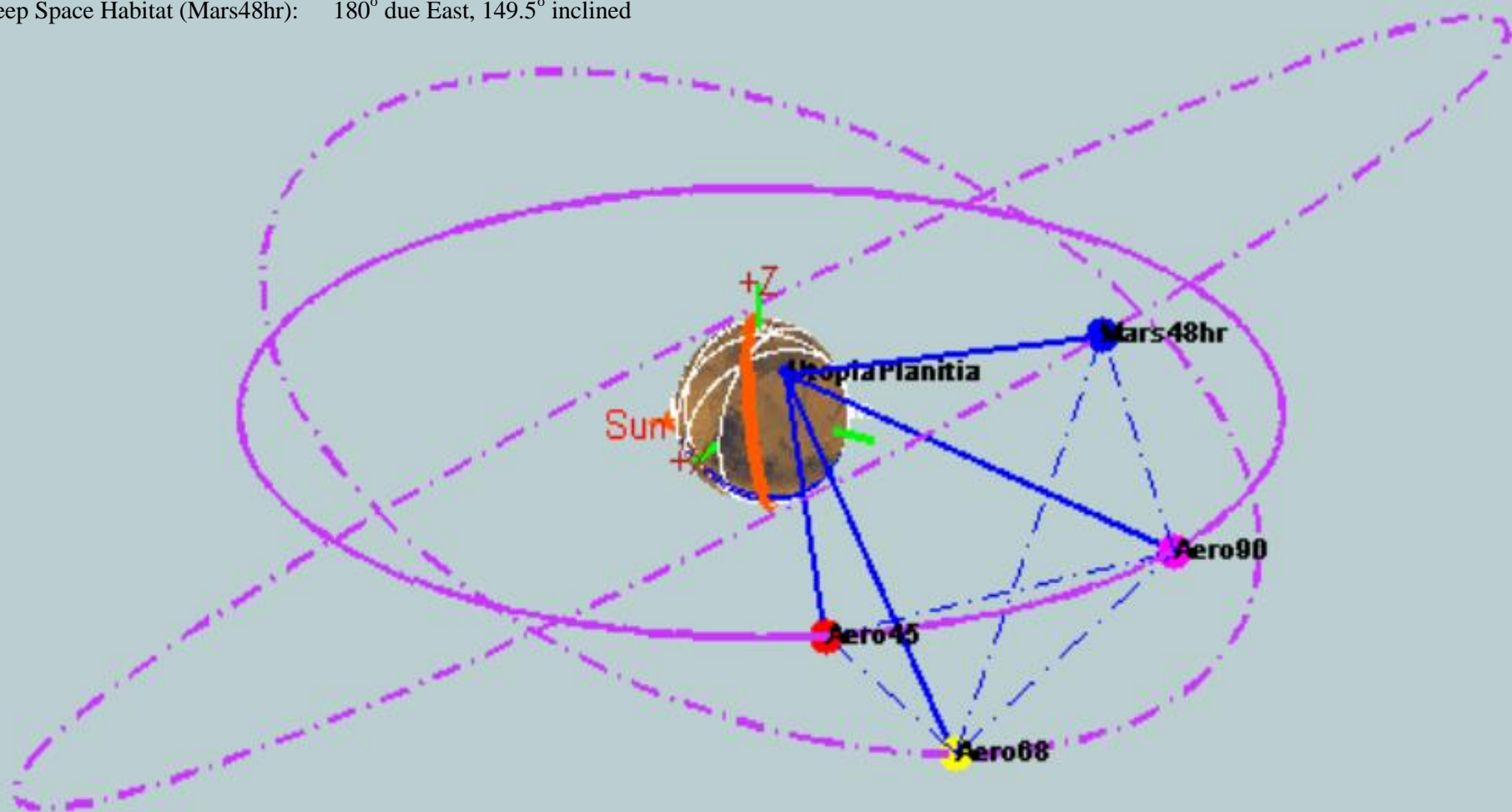


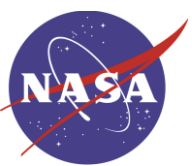


Proposed Mars Regional Navigation Satellite System (3)

Orbits of the Notional Mars Navigation Nodes (3-D View)

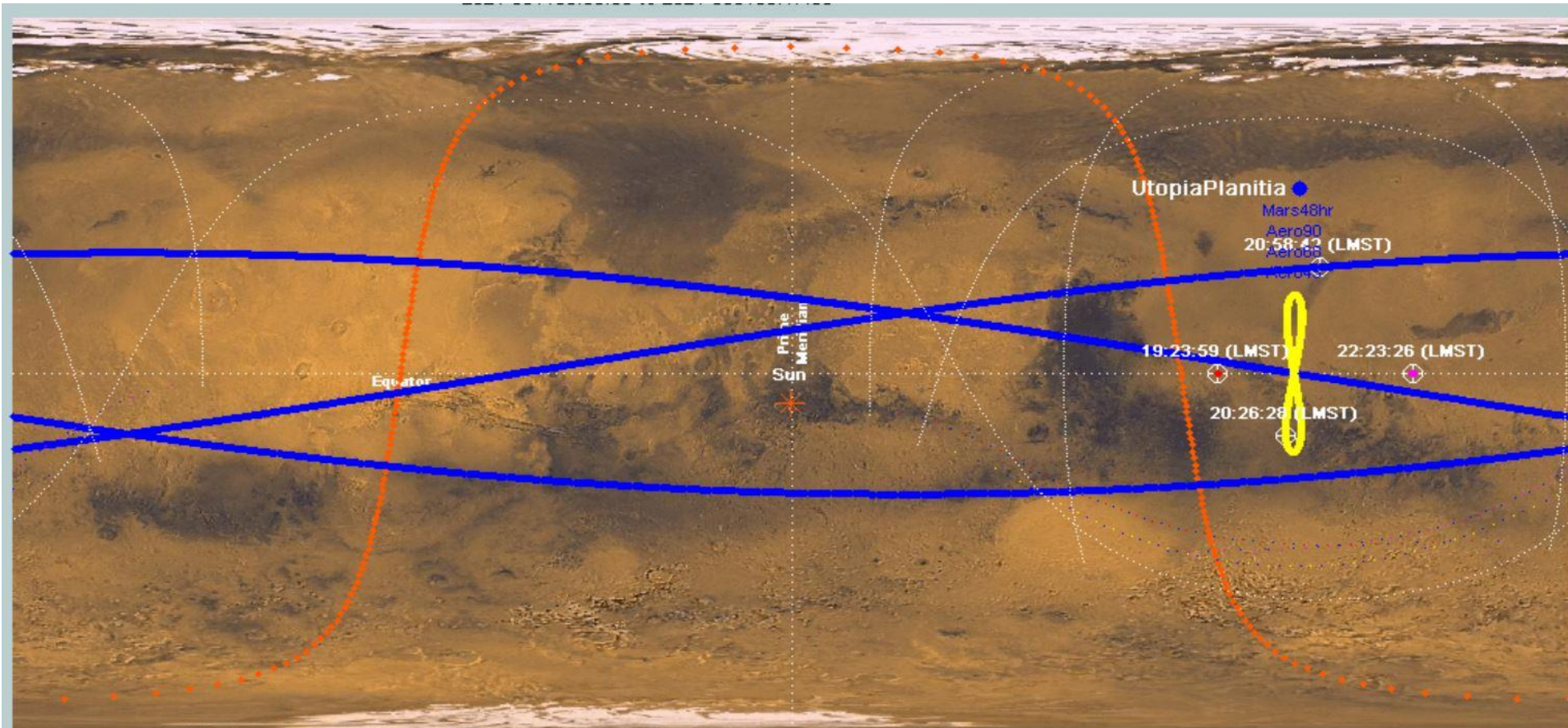
Utopia Planitia: 182.5° due East, 46.7° due North
Aerostationary orbiter 1 (Aero45): 162.5° due East
Aerostationary orbiter 2 (Aero90): 207.5° due East
Aerosynchronous orbiter (Aero68): 180° due East and 20° inclined
Deep Space Habitat (Mars48hr): 180° due East, 149.5° inclined

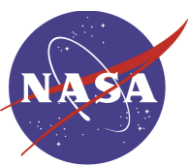




Proposed Mars Regional Navigation Satellite System (4)

Orbits of the Notional Mars Navigation Nodes Projected on Mars Surface (2-D View)





Importance of Accurate Navigation Satellites

Orbit Determination

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0.0m	0.00	3273.85	6547.69	13095.39	32738.48	65476.99	196431.3	229169.9
	0.10m	11.27	3273.70	6547.54	13095.23	32738.32	65476.82	196431.1	229169.7
	0.25m	28.19	3273.56	6547.35	13095.01	32738.08	65476.58	196430.9	229169.5
	0.50m	56.37	3273.51	6547.12	13094.89	32737.71	65476.19	196430.5	229169.1
	1.00m	112.74	3274.15	6547.03	13094.24	32737.04	65475.45	196429.7	229168.3
	2.00m	225.48	3278.35	6548.30	13094.06	32735.98	65474.10	196428.1	229166.7
	5.00m	563.71	3313.95	6563.76	13099.34	32735.15	65471.23	196423.9	229162.4

Table 1. Absolute Localization Error Standard Deviation (cm) of the New Scheme. PDOP=113.17.

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0.0m	14.43	21.57	35.07	65.44	160.06	319.04	956.04	1115.33
	0.10m	21.59	26.82	38.47	67.27	160.75	319.32	956.05	1115.32
	0.25m	42.77	45.58	53.22	76.58	164.76	321.27	956.58	1115.75
	0.50m	81.89	83.33	87.69	103.45	178.67	328.48	958.82	1117.63
	1.00m	161.95	162.62	164.84	173.61	226.38	356.41	968.34	1125.72
	2.00m	323.00	323.28	324.34	328.78	359.12	452.05	1006.71	1158.71
	5.00m	806.95	806.99	807.34	808.99	821.36	865.36	1246.30	1371.59

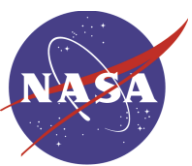
Table 2. Relative Localization Error Standard Deviation (cm) of the New Scheme.
Distance between Reference and Target = 100km. Sigma = 100m. Delta = 100m.

200 – 400 folds
improvement
in RMSE accuracy

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0.0m	0.14	1.59	3.18	6.35	15.87	31.73	95.20	111.07
	0.10m	16.03	16.10	16.32	17.20	22.47	35.45	96.42	112.10
	0.25m	40.08	40.10	40.18	40.53	42.99	50.93	103.02	117.79
	0.50m	80.15	80.16	80.19	80.36	81.59	85.99	123.99	136.48
	1.00m	160.31	160.30	160.32	160.39	160.97	163.19	185.83	194.34
	2.00m	320.62	320.61	320.61	320.63	320.89	321.95	333.77	338.52
	5.00m	801.54	801.53	801.52	801.52	801.58	801.93	806.47	808.38

Table 3. Relative Localization Error Standard Deviation (cm) of the New Scheme.
Distance between Reference and Target = 10km. Sigma = 100m. Delta = 100m.

Sigma: media delay
Delta: clock bias

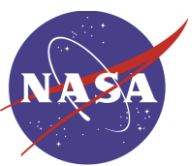


Challenges of Deep Space Tracking/Navigation for Multiple Spacecraft

- Traditional deep space tracking techniques include Doppler, ranging, and delta-DOR
- 2-Way Doppler/ranging requires tight coordination between ground and flight (Doppler compensation), and one ground station tracking one spacecraft (1-to-1)
- Delta-DOR is 1-way, but requires two ground station tracking one spacecraft (2-to-1)
- Tracking requires tying up an antenna for a long time [7]. When number of missions increase, and for missions with multiple spacecraft, there might not be enough DSN antenna assets to meet missions' communications and tracking needs
- There is a desire to extend the current deep space tracking techniques to support multiple spacecraft in a beam to improve the antenna usage efficiency
- Some interesting characteristics:
 - 2-way Doppler and ranging requires tight collaboration between ground and spacecraft. When multiple spacecraft are involved, overall system can be brittle
 - Delta-DOR is one-way, and depends on delays of signal arrival. Overall system is more robust



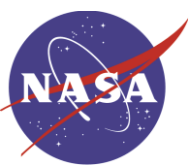
Part 2: 2-Way Simultaneous Doppler/Ranging



Simultaneous Doppler/Ranging: System Approach

A Collaborative Flight-Ground Architecture (1)

- Assume Doppler/ranging in X-band, which supports low rate commands/telemetry
 - The Mars orbiters all lie within the same beamwidth of a DSN 34-m BWG antenna
 - For N orbiters, the downlinks operate in N allocated frequency bands separated by $N-1$ guard bands to prevent interference
 - Collaborative flight-ground architecture:
 - The N orbiters time-share a single uplink; commands differentiated by SCID
 - The ground “Doppler-compensates” the uplink signal in either way:
 - With respect to the Mars center
 - With respect to the average (centroid) of Doppler’s of N orbiters
- Guard bands must be wide enough to accommodate the residual Doppler. Preliminary simulations: residual Doppler and Doppler rate are bounded by 45 KHz & 2.6 Hz/s



Simultaneous Doppler/Ranging: System Approach

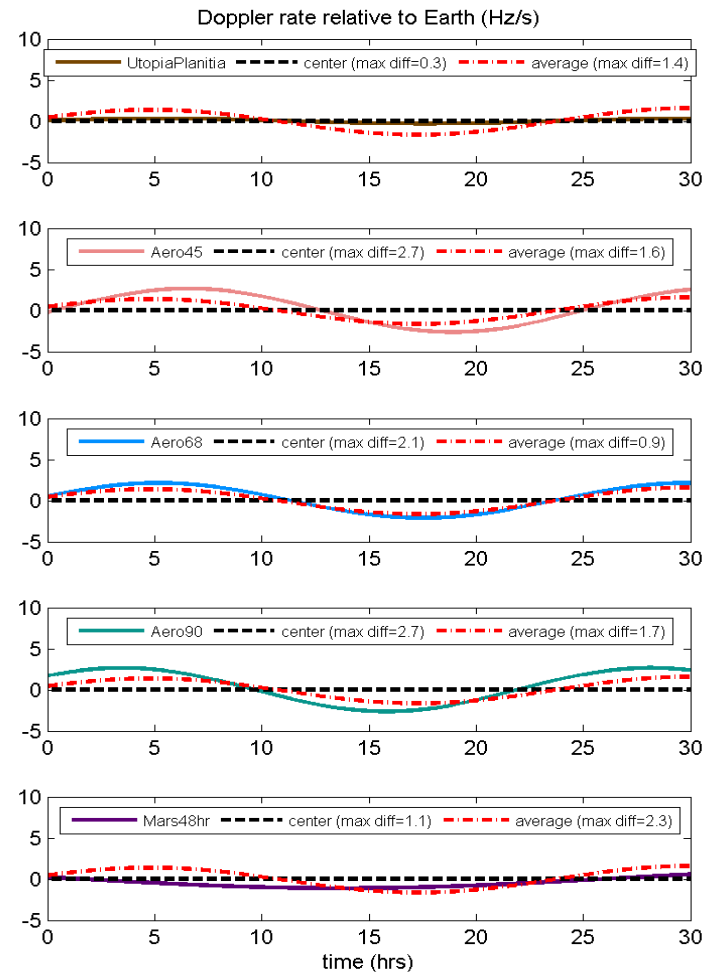
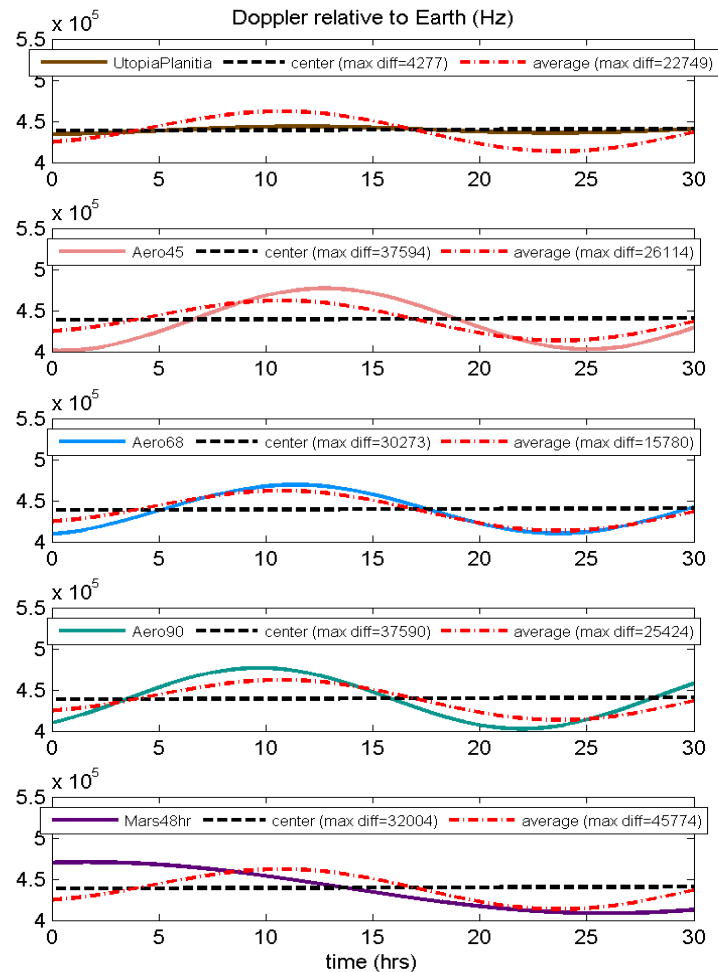
A Collaborative Flight-Ground Architecture (2)

- Flight radio upgrades:
 - A different turn-around-ratio for each spacecraft so the same uplink would be coherently “turned-around” to modulate the telemetry and ranging signals on a different allocated downlink frequency
 - A well-designed tracking loop that can sweep, acquire, and track the unknown uplink carrier phase and high residual Doppler frequency
- Ground upgrades:
 - One ground antenna receives all N downlink signals with different carrier frequencies via Multiple Spacecraft Per Aperture (MSPA)
 - Each signal stream is extracted via band-pass filtering and down-converted to IF for telemetry, Doppler, and range processing



Simultaneous Doppler/Ranging

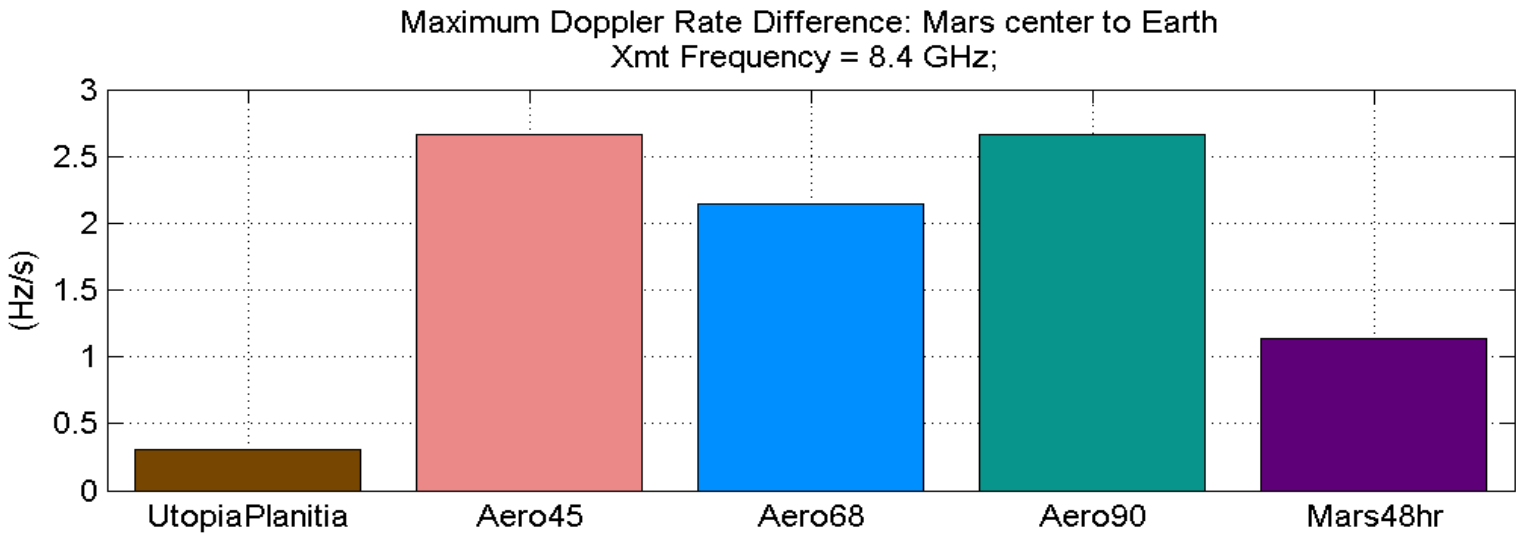
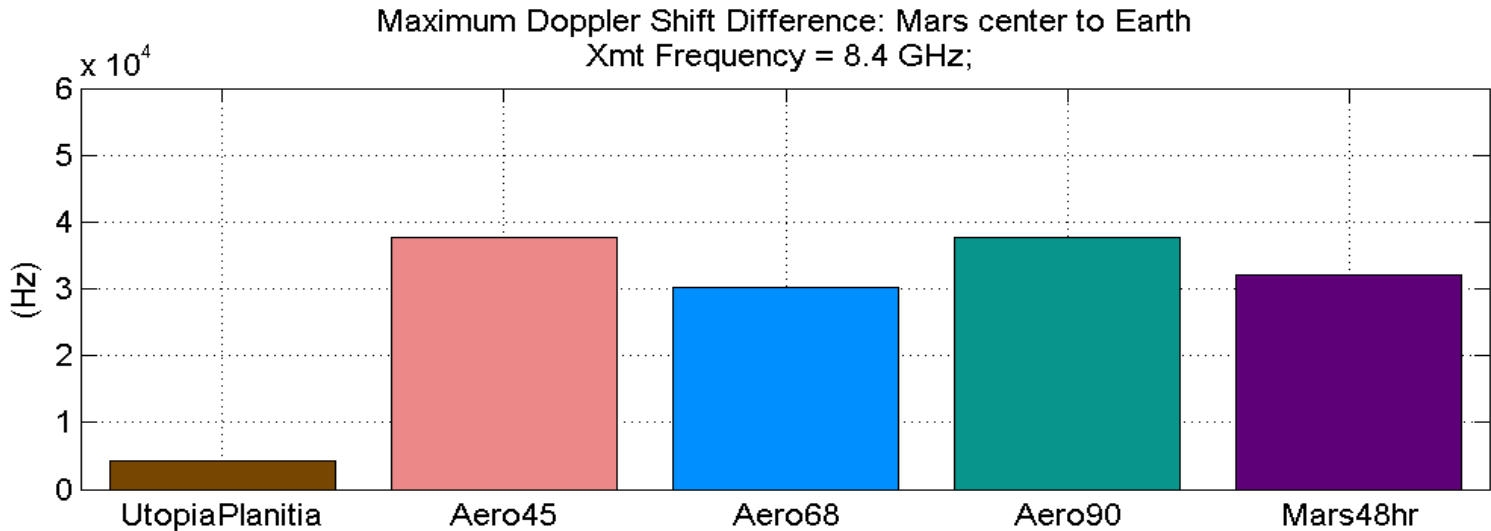
Doppler and Doppler Rate Profiles





Simultaneous Doppler/Ranging

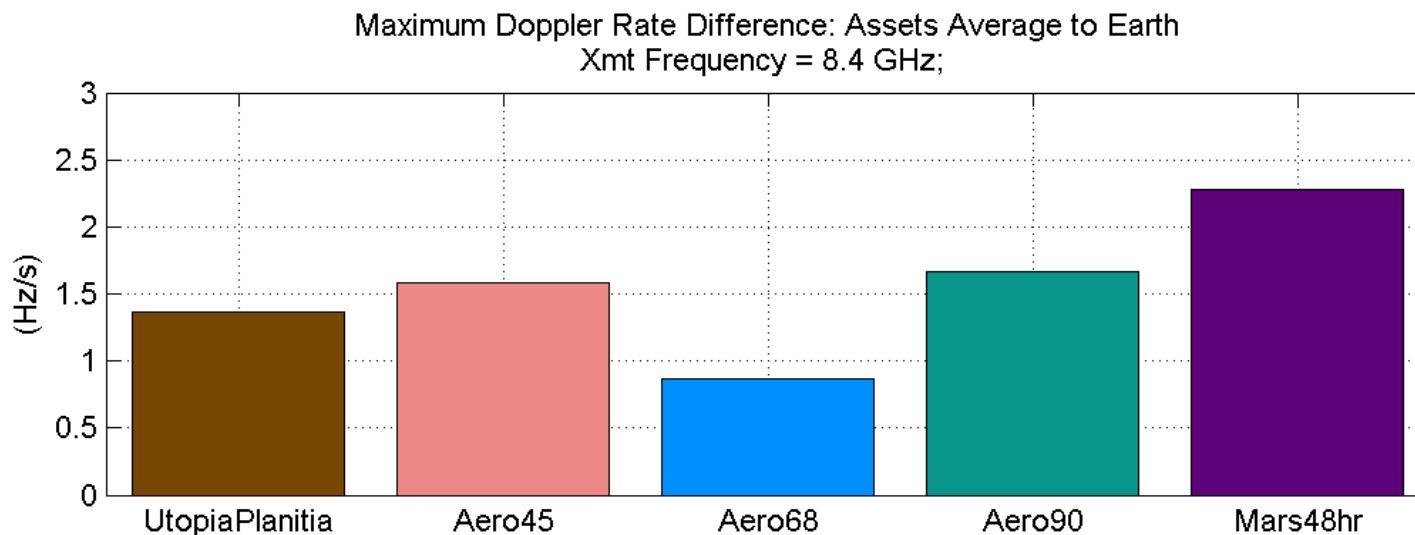
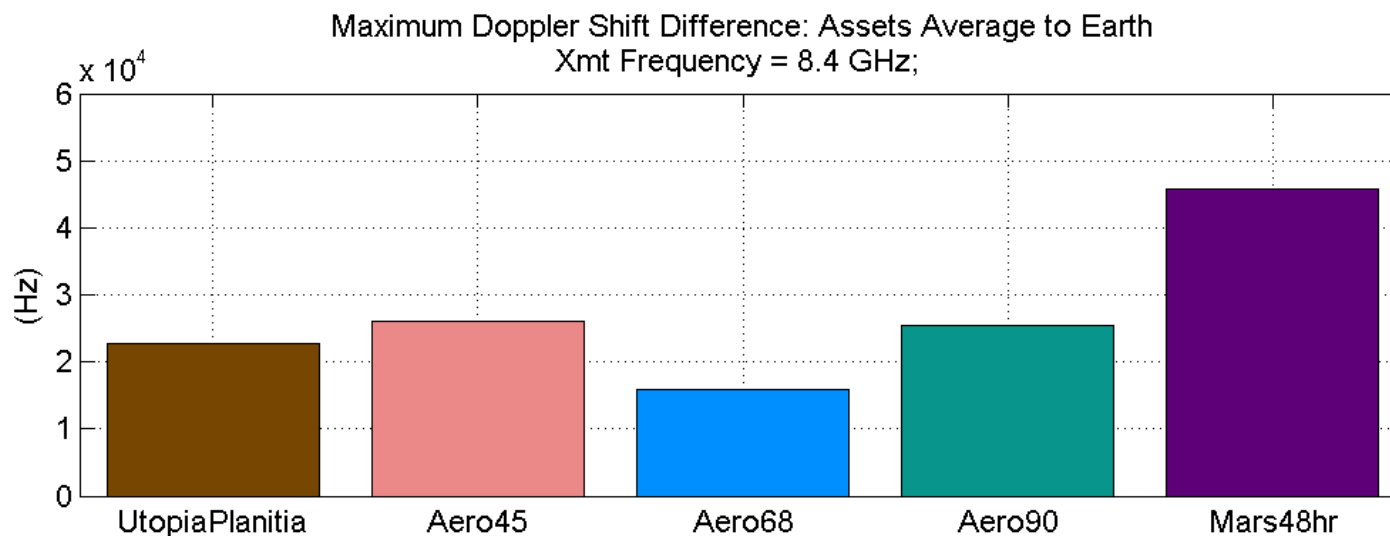
Doppler and Doppler Rate Residuals for Mars Center Strategy

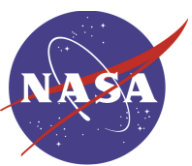




Simultaneous Doppler/Ranging

Doppler and Doppler Rate Residuals for Centroid Strategy





Simultaneous Doppler/Ranging Signal Structure (1)

- Transmitted uplink signal

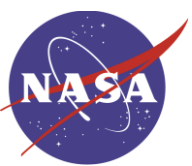
$$S_T(t) = \sqrt{2} \sin[2\rho a_U f_T t + q p_c(t) \sin(2\rho \frac{R_c}{2} t)]$$

- f_T is the uplink carrier frequency, α_u is a function of time that accounts for the Doppler effect on the uplink, $P_c(t)$ is the ranging signal taking values of ± 1 with chip rate R_c , and θ is ranging modulation index
- The range clock is $\frac{R_c}{2} = \alpha_u \beta f_T$, where $b = 2^{-7-C}$ for S-band uplink
 $b = \frac{221}{749} 2^{-7-C}$ for X-band uplink

C is an integer and is a ranging parameter

- The range clock also experience a Doppler effect and appears at the spacecraft with a frequency $\alpha_u \beta f_T$
- The uplink signal after filtering can be represented as

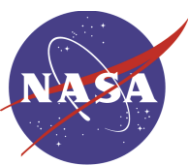
$$S_T(t) = \sqrt{2} J_0(q) \sin[2\rho a_U f_T t] + \sqrt{2} \cos[2\rho a_U f_T t] 2J_1(q) p_c(t) \sin(2\rho \frac{R_c}{2} t) \quad (1)$$



Simultaneous Doppler/Ranging

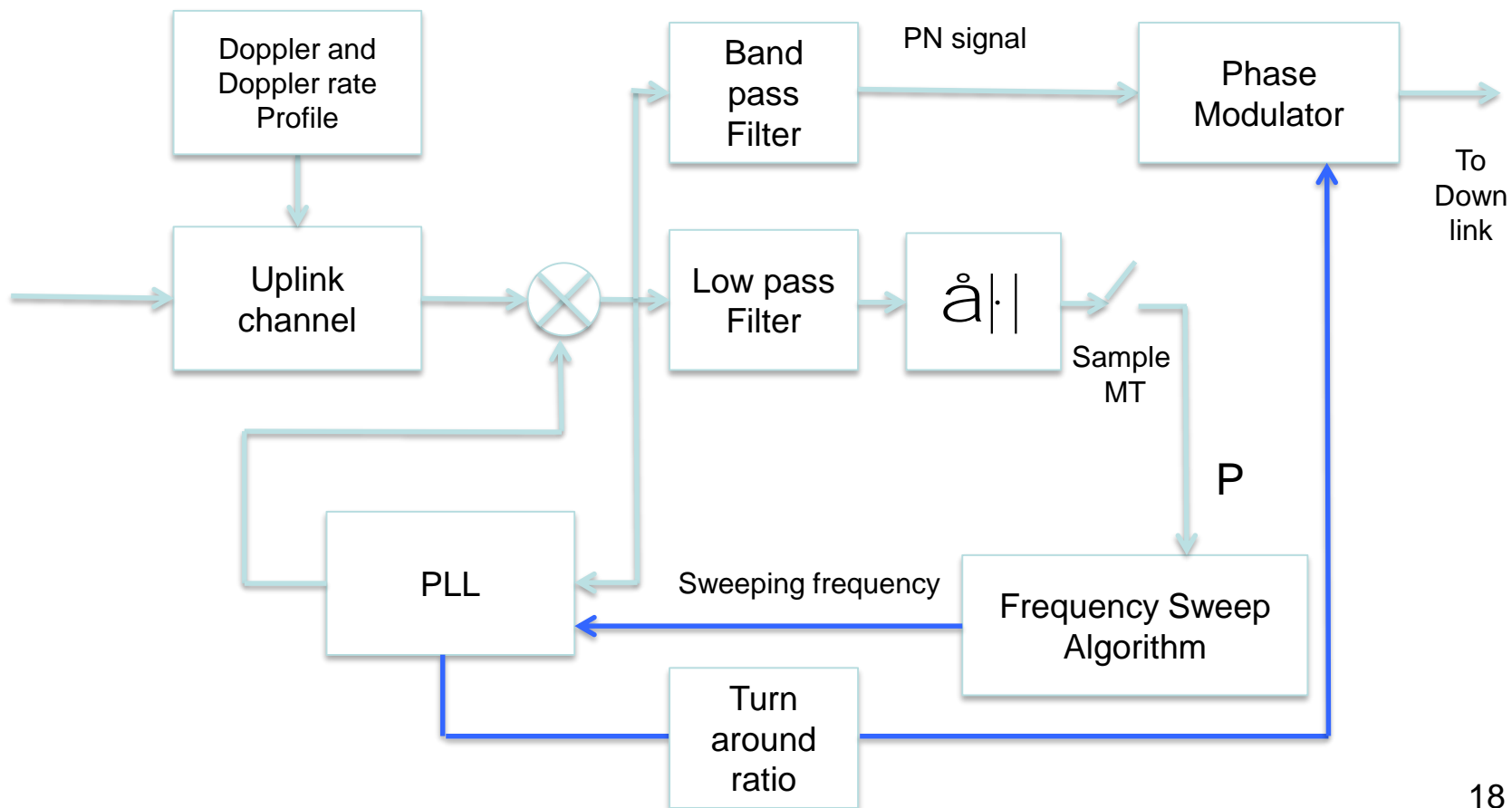
Signal Structure (2)

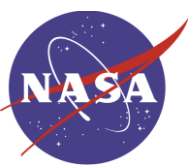
- The PLL provide $\sqrt{2} \cos[2\pi\alpha_u f_T t]$ with any additional non-compensated residual Doppler and Doppler rate. This carrier is used to down convert the 2nd term to baseband to get the ranging signal
- The ranging signal is modulated onto the downlink carrier $\sqrt{2} \sin[2\pi a_u a_D G f_T t]$ where G is the turn-around ratio and α_D is a function of time that accounts for the Doppler effect on the downlink
- Similarly the range clock is $\frac{R_c}{2} = \alpha_u \alpha_D \beta f_T$
- When in-lock the Ground PLL provide $\sqrt{2} \cos[2\pi\alpha_u \alpha_D G f_T t]$. This carrier is used to down convert the received signal to baseband to get the ranging signal
- The ratio of the range clock and the received carrier frequency is β/G
- “Doppler-rate aiding” [9] uses accurate measurements of the downlink carrier frequency provided by the PLL and multiplied with β/G to give an accurate estimate of the received range clock frequency – the rate of change of the range clock phase
- A local model of the received ranging signal is constructed, which has the same rate of change of phase as the received range clock. This Doppler-shifted reference is used to sample the Doppler-shifted ranging signal, producing un-shifted samples for accurate measurements of range



Simultaneous Doppler/Ranging: Spacecraft Radio Schematic

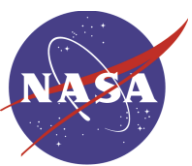
Complex signal representation



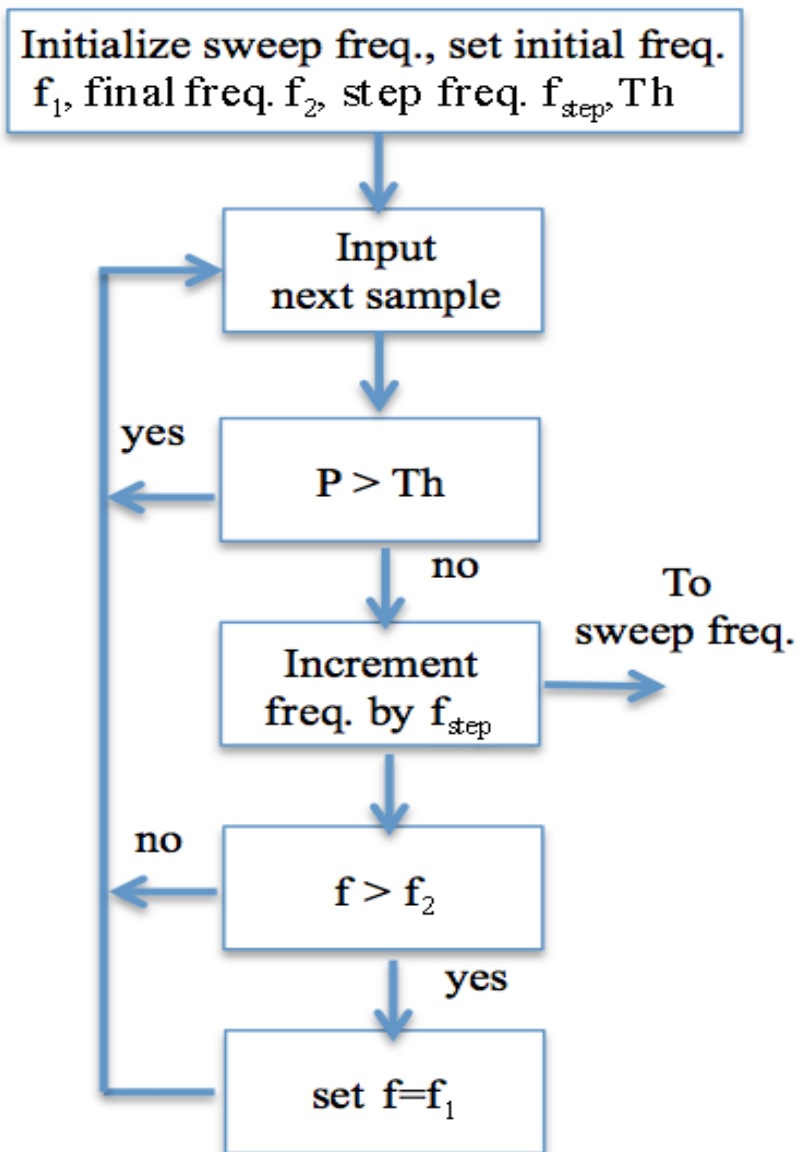


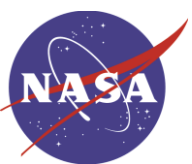
Simultaneous Doppler/Ranging: Smart PLL Tracking

- The first term of (1) is residual carrier and can be tracked with a PLL with a controlled sweeping frequency
- Due to high residual Doppler, a smart sweeping algorithm is needed
 - Other sweeping approaches are FFT and Doppler predicts
- The Electra sweeping approach is static and memoryless (no prior knowledge of past sample)
 - Use constant frequency step f_{step} , move from f_1 (min) to f_2 (max) to compare threshold, and repeat
- The smart sweeping algorithm has the following characteristics:
 - Use multiple thresholds (3), and change f_{step} when a threshold is reached
 - Compare current parameter P_K with P_{K-1} in prior frequency interval to determine the sweeping direction – increase or decrease the sweeping frequency

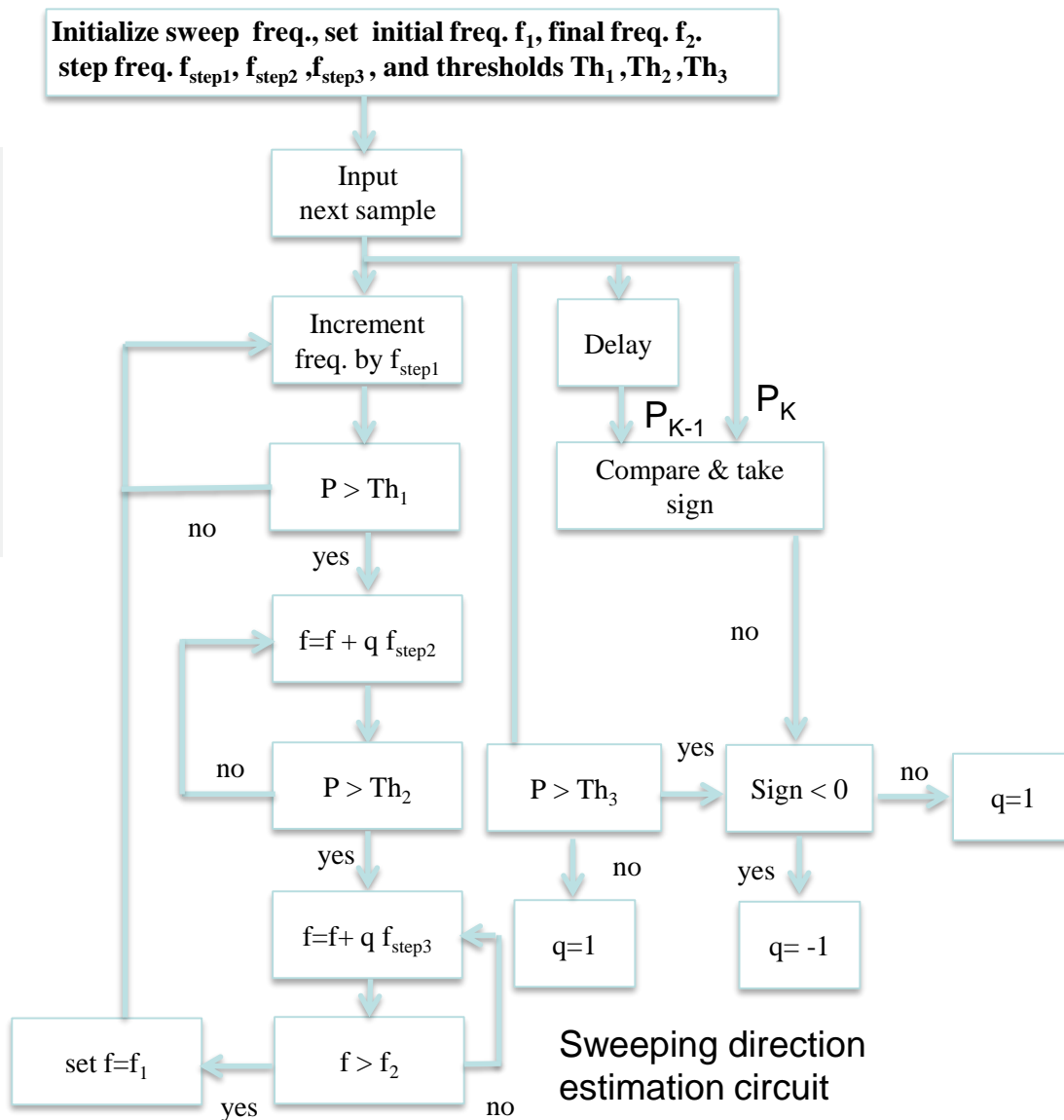
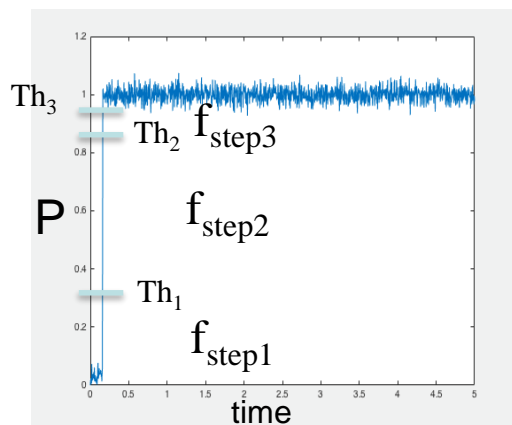


Simultaneous Doppler/Ranging: Current Straight-Forward Electra Sweeping Algorithm

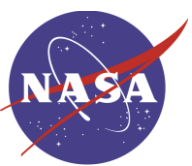




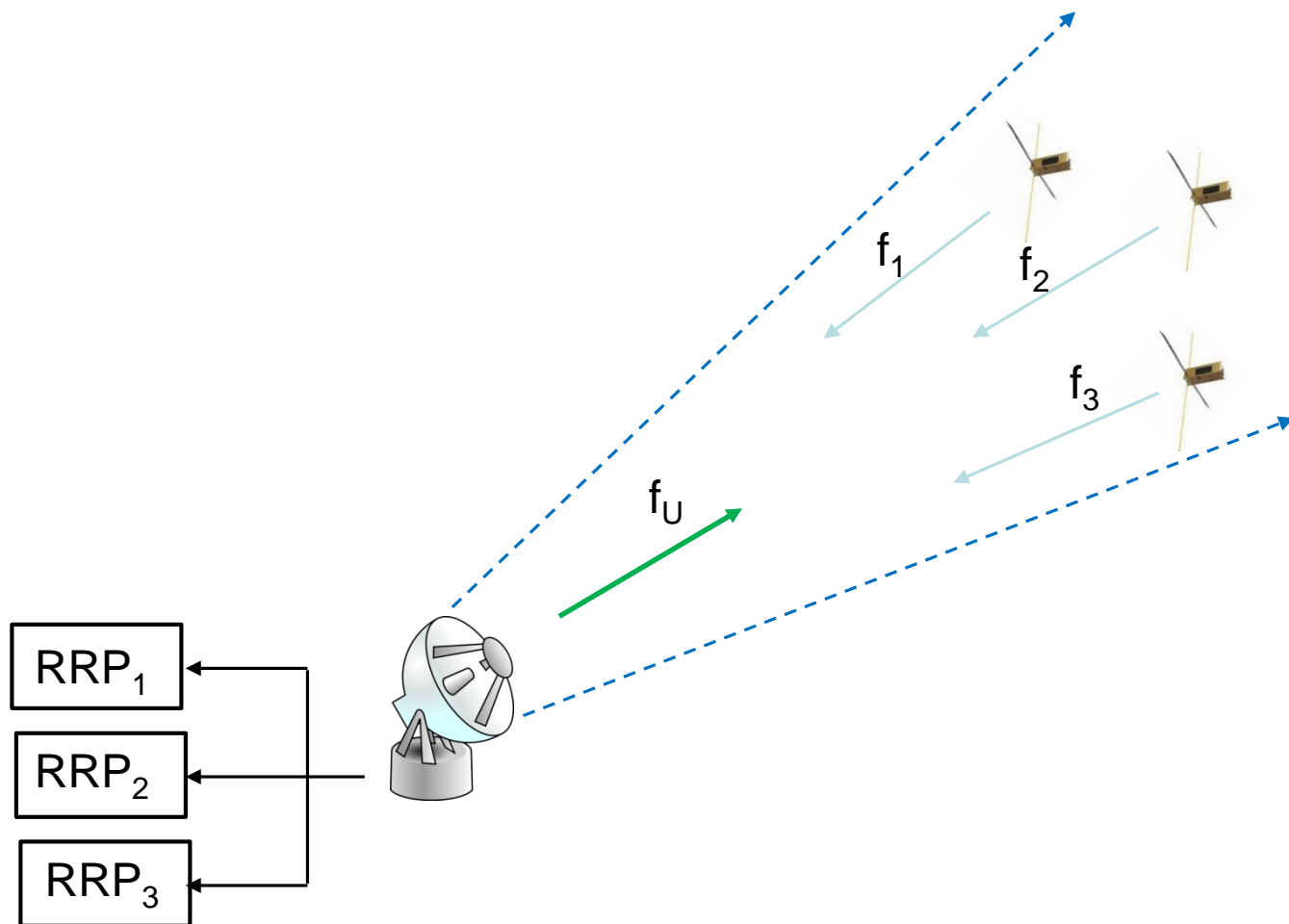
Simultaneous Doppler/Ranging: Flight Radio Smart Frequency Sweeping Algorithm



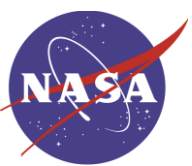
Dynamic sweeping circuit



Simultaneous Doppler/Ranging: High-Level Ground System Schematic and Data Flow



RRP – Receiver Ranging Processor [7]



References

- [1] K.Cheung, C. Lee, "In-Situ Navigation and Timing Services for a Human Mars Landing Site Part 1: System Concept," September 2017, 68th International Astronautical Congress, Adelaide, Australia.
- [2] H. Price, J. Baker, F. Naderi, A Scenario for a Human Mission to Mars Orbit in the 2030s: Thoughts Toward an Executable Program – Fitting Together Puzzle Pieces & Building Blocks, Jet Propulsion Laboratory, California Institute of Technology. Presented at the Future In-Space Operations (FISO) Telecon, May, 2015.
- [3] Mars Architecture Steering Group, Human Exploration of Mars Design Reference Architecture 5.0, Technical Report, NASA, 2009.
- [4] D. Bell, R. Cesarone, T. Ely, C. Edwards, S. Townes, MarsNet: A Mars Orbiting Communications & Navigation Satellite Constellation, IEEE Aerospace Conference 2000, March 2000, Big Sky, Montana.
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- [6] K. Cheung, C. Lee, A Trilateration Scheme for GPS-Style Localization, Interplanetary Network Progress Report, 42-209, May 15, 2017.
- [7] P. Romero, B. Pablos, G. Barderas, "Analysis of Orbit Determination from Earth-Based Tracking for Relay Satellites in a Perturbed Areostationary Orbit," Acta Astronautica 136 (2017) 434-442, April 4, 2017.
- [8] J. Berner, S. Bryant, and P. Kinman, "Range Measurement as Practiced in the Deep Space Network," Proceedings of the IEEE, Vol. 95, No. 11, November 2007